

ARMY RESEARCH LABORATORY

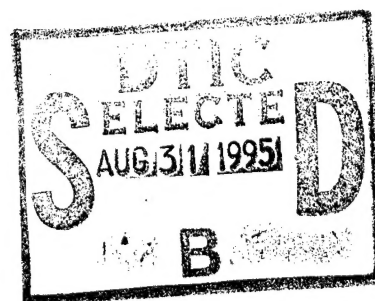


Tomographic Analysis of CO Absorption in Low-Pressure Flame

K. L. McNesby
R. G. Daniel
J. B. Morris
A. W. Miziolek

ARL-TR-769

June 1995



19950830 070

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.

DTIC QUALITY INSPECTED 8

NOTICES

Destroy this report when it is no longer needed. DO NOT return it to the originator.

Additional copies of this report may be obtained from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The use of trade names or manufacturers' names in this report does not constitute endorsement of any commercial product.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE June 1995		3. REPORT TYPE AND DATES COVERED Final, 1 March-1 November 1994
4. TITLE AND SUBTITLE Tomographic Analysis of CO Absorption in Low-Pressure Flame			5. FUNDING NUMBERS PR: 1L161102AH43	
6. AUTHOR(S) K. L. McNesby, R. G. Daniel, J. B. Morris, and A. W. Miziolek				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: AMSRL-WT-PC Aberdeen Proving Ground, MD 21005-5066			8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-769	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES This work was supported by the Strategic Environmental Research and Development Program (SERDP).				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Tomographic analysis is used to provide a correction to low-pressure, burner stabilized, stoichiometric premixed CH ₄ /O ₂ flame temperatures measured using tunable diode laser (TDL) absorption spectroscopy employing CO two-line thermometry. It is shown that flame temperatures measured using line-of-sight-based two-line thermometry are always too low, and that the correction to the observed temperature is a nonlinear function of the height above the burner surface. It is also shown that at a given height in the flame, a constant temperature across the flame does not imply that vibrational populations are constant, and that at low pressures (<20 torr), the flame spreads radially beyond the burner diameter so that it may no longer be approximated by a one-dimensional model without application of an area correction.				
14. SUBJECT TERMS diode laser spectroscopy, optical tomography, two-line thermometry, tomography, spectroscopy, tunable diode laser, temperature measurement, absorption spectroscopy			15. NUMBER OF PAGES 26	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

INTENTIONALLY LEFT BLANK.

TABLE OF CONTENTS

	<u>Page</u>
LIST OF FIGURES	v
1. INTRODUCTION	1
2. BACKGROUND	2
3. EXPERIMENTAL	4
3.1 Apparatus	4
3.2 Data Analysis	5
4. RESULTS AND DISCUSSIONS	8
5. CONCLUSION	13
6. REFERENCES	15
DISTRIBUTION LIST	17

Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

INTENTIONALLY LEFT BLANK.

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1. The line-of-sight path through the low-pressure containment chamber as viewed from above the apparatus. Gas densities and temperatures may differ greatly in going from the exhaust gas region into the shroud gas region into the flame region	1
2. Temperatures measured using two-line thermometry and a Pt/Pt-10%Rh thermocouple show different temperature vs. height above burner surface contours. Thermocouple temperatures have been corrected for emissivity	3
3. Moving the line-of-sight path to different values of the lateral coordinate, x , allows different line-of-sight absorbances, $g(x)$ to be measured (see text)	6
4. CO hot band absorbance in a 20-torr stoichiometric methane/oxygen flame	9
5. Line-of-sight integrated absorbance for CO P19 ($v=1 \rightarrow 2$) in a 20-torr stoichiometric methane/oxygen flame as a function of off-axis distance using a laser beam diameter of 0.8 mm. All spectra were measured through a plane lying 5.2 mm above the burner surface. The edge of the burner is at -30 and 30 mm. Data have been reflected about the burner axis	9
6. Results of tomographic analysis on line-of-sight CO absorbance spectra lying in a plane 0.8 mm thick and 4.19 mm above the burner surface for a 20-torr stoichiometric methane/oxygen flame. Note that a constant temperature is seen across the burner face even though the populations of P19 ($v=1 \rightarrow 2$) and P13 ($v=2 \rightarrow 3$) are not constant. Data have been reflected about the burner axis	10
7. The fraction of CO $v=1 \rightarrow 2$ absorbance which lies within the flame region as a function of height above the burner surface for a 20-torr stoichiometric methane/oxygen flame	11
8. The fraction of CO $v=2 \rightarrow 3$ absorbance which lies within the flame region as a function of height above the burner surface for a 20-torr stoichiometric methane/oxygen flame	12
9. Uncorrected and corrected flame temperatures measured using line-of-sight two-line thermometry and using thermocouples as a function of height above the burner surface for a 20-torr stoichiometric methane/oxygen flame	13

INTENTIONALLY LEFT BLANK.

1. INTRODUCTION

Absorbances measured using line-of-sight techniques inherently report spectral attenuation integrated along the entire beam path (Limbaugh 1985). At a given frequency, line-of-sight absorbance through a low-pressure combustor system may have contributions from gases at several different densities and temperatures corresponding to the light beam passing through different regions in the low-pressure containment chamber. The degree to which the line-of-sight path is nonhomogeneous is determined by diffusion and flow dynamics within the flame and low-pressure containment chamber. Usually, the region of interest is the flame region where the density of some combustion gases may be less than in cooler portions of the line-of-sight path. This situation is illustrated in Figure 1.

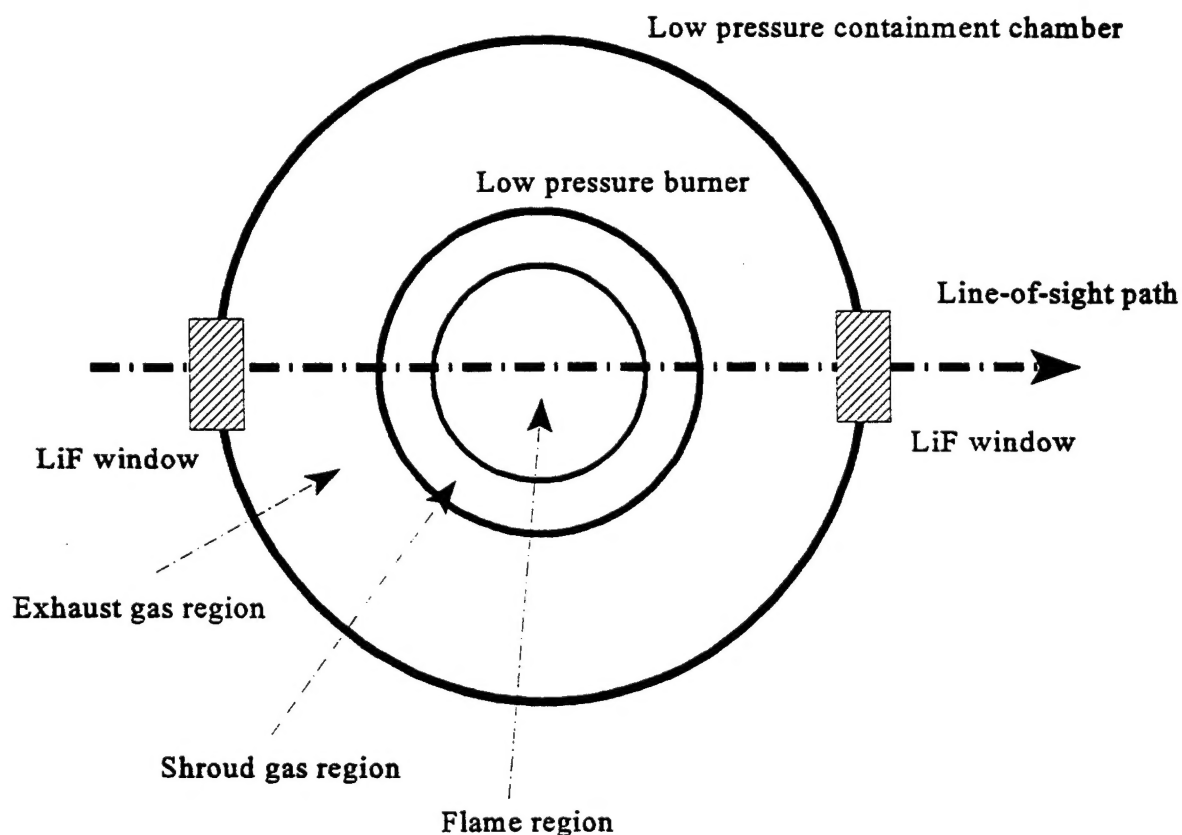


Figure 1. The line-of-sight path through the low-pressure containment chamber as viewed from above the apparatus. Gas densities and temperatures may differ greatly in going from the exhaust gas region into the shroud gas region into the flame region.

Several methods have been developed to minimize contributions to measured absorbance arising from species outside the region of interest of the line of sight. These range from instrumental techniques such as "onion peeling" (Dasch 1992) and tomographic analysis (Cormack 1963), to restricting observation to species or states of species that minimize potential errors or may only exist in the line-of-sight region of interest (Dayton et al. 1993). A common method of measuring temperature using absorbance spectra employs tunable diode laser (TDL)-based, two-line thermometry (Hanson and Falcone 1978; Schoenung and Hanson 1981). In this method, temperature is calculated by fitting the integrated absorbance of two close-lying rovibrational transitions originating from different vibrational states to a Boltzmann distribution.

To minimize errors in temperature measured by two-line thermometry, it is important to minimize the degree of flamespreading, and hence the amount of absorbing gas, beyond the burner surface diameter. This has been shown (Jeffries et al. 1992) to be most easily accomplished by keeping total pressure within the flame chamber above 30 torr. Unfortunately, raising the total pressure causes flame regions to become more compact, limiting spatial resolution. Spectral lines selected for the analysis should have the largest separation of initial energy states possible to maximize temperature sensitivity (Ouyang and Varghese 1990). It is also necessary to maximize the ground state energy of the most intense transition so as to minimize the effect of "cold gas" absorbance.

2. BACKGROUND

In our experiments, we have measured temperatures and species concentration profiles in a 20-torr premixed CH_4/O_2 flame as a function of height above the surface of a flat flame burner. Species concentrations are measured using line-of-sight TDL infrared absorption spectroscopy. Temperatures are measured using TDL-based, two-line thermometry and a fine-wire Pt/Pt-10%Rh thermocouple. Temperature is measured using two complementary methods because of limitations associated with each technique. For thermocouple measurements, the main limitation is that the thermocouple wire must enter the flame, and this perturbation may cause the measured temperature to be in error. For two-line thermometry, the main limitation is that the technique is a line-of-sight measurement in which absorbance is integrated along the entire light path. Additionally, for compact flame zones, the probe laser beam diameter may be large enough to sample regions of high temperature variance.

As an example of the discrepancy that may exist between results obtained by these complementary methods, Figure 2 shows flame temperatures as a function of height above the burner surface for a 20-torr premixed CH_4/O_2 flame measured by two-line thermometry and by a thermocouple. The thermocouple temperatures have been corrected for radiative emission (Sausa et al. 1990). Figure 2 indicates that the temperature as a function of height above the burner surface in a 20-torr premixed CH_4/O_2 flame rises faster when measured using two-line thermometry than when measured using a thermocouple. Conversely, the overall temperature of the same flame is found to be at a higher temperature and the peak temperature at a distance further from the burner surface when measured by a thermocouple than when measured using two-line thermometry. This report addresses the latter discrepancy by using tomographic analysis to provide a correction to line-of-sight spectra for this combusting system.

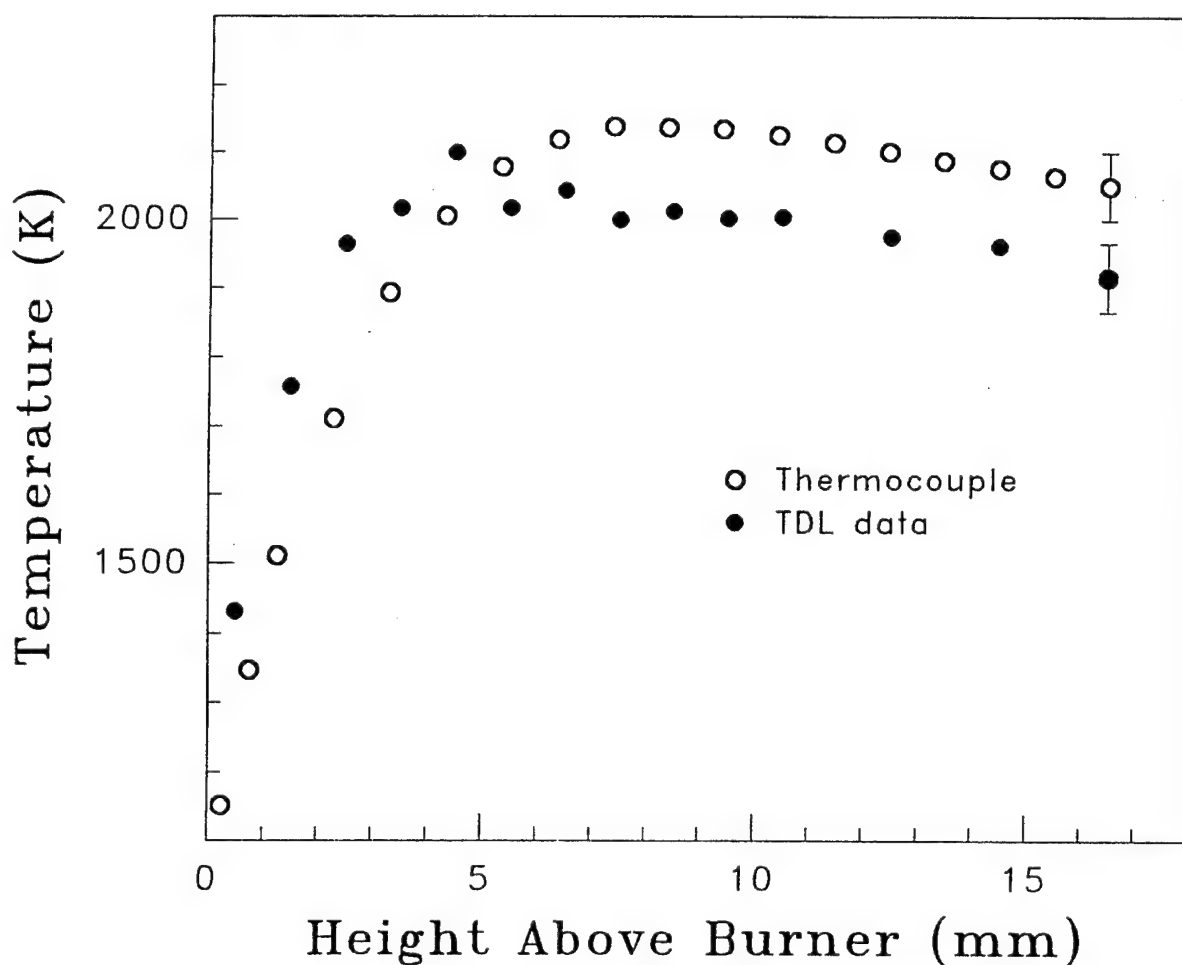


Figure 2. Temperatures measured using two-line thermometry and a Pt/Pt-10%Rh thermocouple show different temperature vs. height above burner surface contours. Thermocouple temperatures have been corrected for emissivity.

3. EXPERIMENTAL

3.1 Apparatus. The experimental apparatus has been extensively described in a previous publication (McNesby and Fifer 1992). Briefly, the apparatus consists of a low-pressure flat flame burner (McKenna Industries, Inc.) mounted on translational stages inside an evacuable chamber. The evacuable chamber is equipped with LiF windows (apertured to 800 μm diameter) to allow passage of infrared laser radiation. Since the infrared laser beam remains fixed in position, different parts of the flame are examined by moving the burner within the chamber relative to the laser beam path.

Laser radiation is provided by a helium-cooled TDL (Laser Photonics, Analytics Division) and detected using liquid-nitrogen-cooled HgCdTe infrared detectors. Laser output is collimated, mode and coarse frequency selected, and chopped prior to entering the low-pressure chamber. Lock-in detection at the chopping frequency effectively discriminates against emission from the flame. Entrance and exit apertures mounted on the evacuable burner chamber restrict the maximum beam diameter through the flame to 800 μm . For concentration and two-line thermometry measurements, the laser was scanned over two pairs of CO transitions (Todd et al. 1976) (P18 $\nu=1\rightarrow2$ at 2042.9972 cm^{-1} ; P12 $\nu=2\rightarrow3$ at 2042.8085 cm^{-1} and P13 $\nu=2\rightarrow3$ at 2038.6249 cm^{-1} ; P19 $\nu=1\rightarrow2$ at 2038.5822 cm^{-1}). These line pairs were selected because they required the smallest scanning range within the specified output of our laser system ($\sim 2030\text{--}2060\text{ cm}^{-1}$), because absorption from a vibrationally excited state is minimized in room temperature CO, and because these lines conformed to previously published criteria for two-line thermometry experiments (Ouyang and Varghese 1990). Linearity of the laser frequency versus tuning current was checked using a confocal etalon and also by visual examination of room temperature CO absorption profiles. It was found that for the small tuning range of these experiments ($\sim 0.2\text{ cm}^{-1}$) no correction was necessary to account for nonlinearity of laser frequency with tuning current. All flames studied were stoichiometric CH_4 (0.95 liters/min)/ O_2 (1.9 liters/min) flames surrounded by an Ar (3 liters/min) shroud. Total pressure within the burner chamber was maintained at 20 torr.

Thermocouple temperature profiles were measured using 100- μm Pt/Pt-10%Rh thermocouples coated with a refractory mixture of yttrium oxide and beryllium oxide (Kent 1970). The refractory coating is necessary primarily to promote radiative cooling of the interior of the thermocouple wire and also to inhibit any catalytic reactions that may occur at the platinum surface. Temperatures were measured with the thermocouple junction at the center of the flame. The thermocouple was withdrawn from the flame

region when line-of-sight spectra were measured. Measured thermocouple temperatures were corrected for radiative heat losses (Sausa et al. 1990).

3.2 Data Analysis. It was assumed that all flames investigated possessed axial symmetry. Scans at equal distance from either side of the flame center showed the flame to be axisymmetric to within the accuracy of the experiment. The data collection scheme was as follows. Starting at a fixed height above the burner surface, a transmission spectrum was measured. The horizontal motion stage was then translated 2 mm, and another scan measured. This process was repeated until 20 parallel transmission spectra had been recorded. The TDL probe beam diameter was 800 μm . The initial scan was through the center of the flame, with each successive scan closer to the perimeter of the flame. Since the burner radius is 30 mm, this data collection scheme provides five scans outside a cylinder defined by the burner circumference. This is necessary to examine contributions to line-of-sight absorbance by CO in regions of the flame that have spread radially beyond the burner surface diameter.

The tomographic analysis of the line-of-sight spectra employed a 3-point Abel inversion that has recently appeared in the literature and is available in spreadsheet form (Dasch 1992), although several other methods were also tried and gave similar results (Deutsch and Beniaminy 1983). Absorbance data were used in all inversion routines. For an axisymmetric flame, it is assumed that at any height above the burner surface, temperatures and species concentrations have only radial dependence. Any species or temperature gradients may then be mapped as a series of concentric circles centered about the burner axis.

Tomographic analysis as employed here uses a series of parallel line-of-sight absorbance spectra at a given height in the flame to obtain the radial dependence of species concentration and temperature at that height. The line-of-sight absorbance at a given frequency for a single absorbing species through an optically thin, axisymmetric medium may be given by (Cornack 1982):

$$g(x) = \frac{2 \int_0^x f(r) r dr}{(r^2 - x^2)^{1/2}} \quad (1)$$

where $g(x)$ is the line-of-sight absorbance through the medium at lateral position x , and $f(r)$ is the product of the absorption coefficient and the partial pressure at radial position r within the axisymmetric medium. If more than one species absorbs at this frequency, then $f(r)$ would be a sum of absorption coefficients times partial pressures. The previous equation may be solved for $f(r)$ using the Abel transformation:

$$f(r) = -\frac{1}{\pi} \int_r^1 \frac{g'(x) dx}{(x^2 - r^2)^{1/2}} \quad (2)$$

where $g'(x)$ denotes the derivative with respect to x of the function $g(x)$. Spatial resolution of $f(r)$ is determined by the diameter of the infrared laser beam (800 μm). This method of analysis is shown schematically in Figure 3. Problems and limitations of analyzing line-of-sight data using Abel inversion techniques have been discussed previously in the literature (Best et al. 1991).

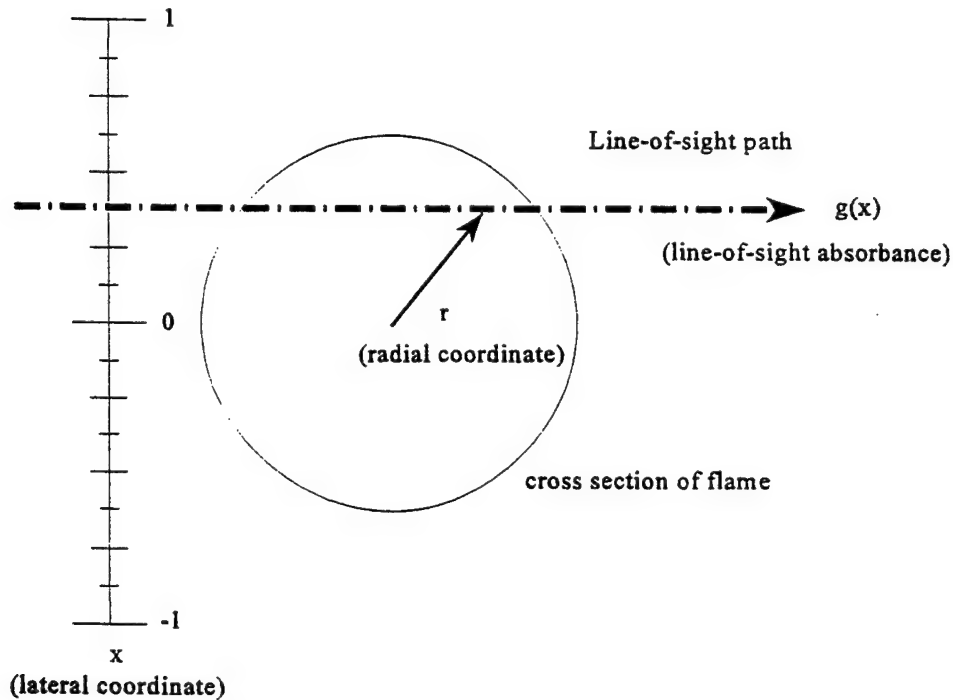


Figure 3. Moving the line-of-sight path to different values of the lateral coordinate, x , allows different line-of-sight absorbances, $g(x)$ to be measured (see text).

The error in the tomographic analysis employed here was estimated by generating synthetic line-of-sight data for a "perfect" flat flame (which would have a uniform radial CO distribution across the burner face and no CO beyond the burner face radius) and then using the 3-point Abel inversion to retrieve the parameters used to originally generate the synthetic data. Tomographic analysis of these synthetic data sets showed a small systematic error for values of localized absorbance at the edge of the flame, near the region of the largest change in localized CO absorbance with radial position. The nature of the error was

to overestimate the species distribution at the flame edge by approximately 5%. However, the Abel inversion technique did not report localized absorbance outside of the synthetic flame region. Also, the effect of absorption of light by CO outside of the optically accessible 40-mm radius was found to have a significant effect on reported localized absorbance within the optically accessible area. Since the absorbance from the hot band transitions used here was vanishingly small outside of the optically accessible region, we do not believe this to be an important source of error. A discussion of errors in tomographic reconstruction is beyond the scope of this report and has been discussed elsewhere for the case of one-dimensional systems (Best et al. 1991). We do believe that it is necessary to examine the effect of the inversion technique on synthetic data that approximates each system to be examined.

For the data analysis employed here, raw transmittance spectra for each scan were rationed to an artificial baseline constructed from nonabsorbing portions of each spectrum. A new baseline was constructed for each individual scan. This procedure was necessary because of the continual drift of the TDL output with time. Normally, compensation for this drift is accomplished by sampling a portion of the laser output with a pellicle beamsplitter and simultaneously collecting a background scan. However, for our apertured line of sight, it was found that the slight beam walk (caused by the grating used to coarse select the laser frequency) across the low-pressure chamber entrance aperture during laser frequency scanning made obtaining a simultaneous output matched background spectrum difficult.

The transmittance spectrum obtained using the synthetic baseline was then converted to absorbance, and each spectral feature fit to a Voigt line shape (which just happens to describe the data well) to obtain an integrable function. Since we are assuming variance of CO temperature and density along the line of sight, no inferences in this are drawn from the values of the Voigt fit parameters. An alternative method was to collect a background spectrum with the flame off at the end of a set of parallel scans. When using this method, it was necessary to employ a baseline correction following conversion to absorbance prior to fitting a Voigt function to the data. Both methods of obtaining absorbance spectra gave similar results. The fitted spectrum was then integrated and the results used as input to the Abel inversion routine. Again, it should be emphasized that for the tomographic analysis, the Voigt function was used only to obtain an integrable function that described the data. An additional reason for using the Voigt function to approximate the observed data is that a fit of both peaks in the measured spectrum results in deconvolution of the line shapes, minimizing integration errors caused by line overlap.

For the two-line thermometry experiments where uniform conditions along the line of sight were implicitly assumed (the "corrected" line-of-sight measurements), CO temperature and concentration were varied in an expression for the Voigt line shape until a best fit to the observed data for the two lines observed in the spectrum was obtained. The areas underneath the individual peaks of the fitted spectrum were used for the final temperature calculation. In this way, both rovibrational and translational manifestations of the temperature were used in the determination (Varghese 1980). Typically, 2,048 data points were collected over a scan range of 0.1 cm^{-1} for an effective resolution (Rayleigh criterion) of approximately 0.0005 cm^{-1} . At 2,000 K, the line width (Guelachvili et al. 1992) (FWHM) for CO rovibrational transitions originating from an excited vibrational state is approximately 0.05 cm^{-1} .

4. RESULTS AND DISCUSSIONS

Figure 4 shows an absorbance spectrum of CO through the center of a 20-torr CH_4/O_2 flame. The line of sight is 5.2 mm above the burner surface using an 800- μm -diameter infrared laser beam. Figure 5 shows the line-of-sight integrated absorbance for CO P19 $v=1\rightarrow 2$ (the large peak in Figure 4) in the 20-torr CH_4/O_2 flame as a function of the radial distance from the burner center to the line of sight. Spectra were measured at a constant height of 5.2 mm above the burner surface. This figure is a graphical representation of the data input into the Abel inversion routine. Since the edge of the burner surface lies at -30 and $+30$ mm, CO absorbance outside of this region is assumed to be from gas outside of the cylinder defined by the burner circumference. From Figure 5, it is clear that there is significant line-of-sight absorbance for the CO (P19 $v=1\rightarrow 2$) transition from hot CO gas outside of the region defined by the burner circumference.

Figure 6 shows the results of tomographic analysis of line-of-sight absorbance spectra through a 20-torr CH_4/O_2 flame, with the line of sight contained within a plane 800 μm thick and 4.19 mm above the burner surface. The tomographic analysis indicates that the distribution of population in the first and second excited vibrational states (assuming rotational equilibrium) within the line-of-sight plane is not uniform. From reconstructions using synthetic line-of-sight data, we estimate the uncertainty in the localized CO distribution to be less than 5%. The increase in localized CO density at the edges of the flame was observed for all heights studied.

The ratio of localized integrated absorbance of P13 ($v=2\rightarrow 3$) to P19 ($v=1\rightarrow 2$) is also shown in Figure 6. This ratio is nonlinearly proportional to the rovibrational flame temperature at this position in

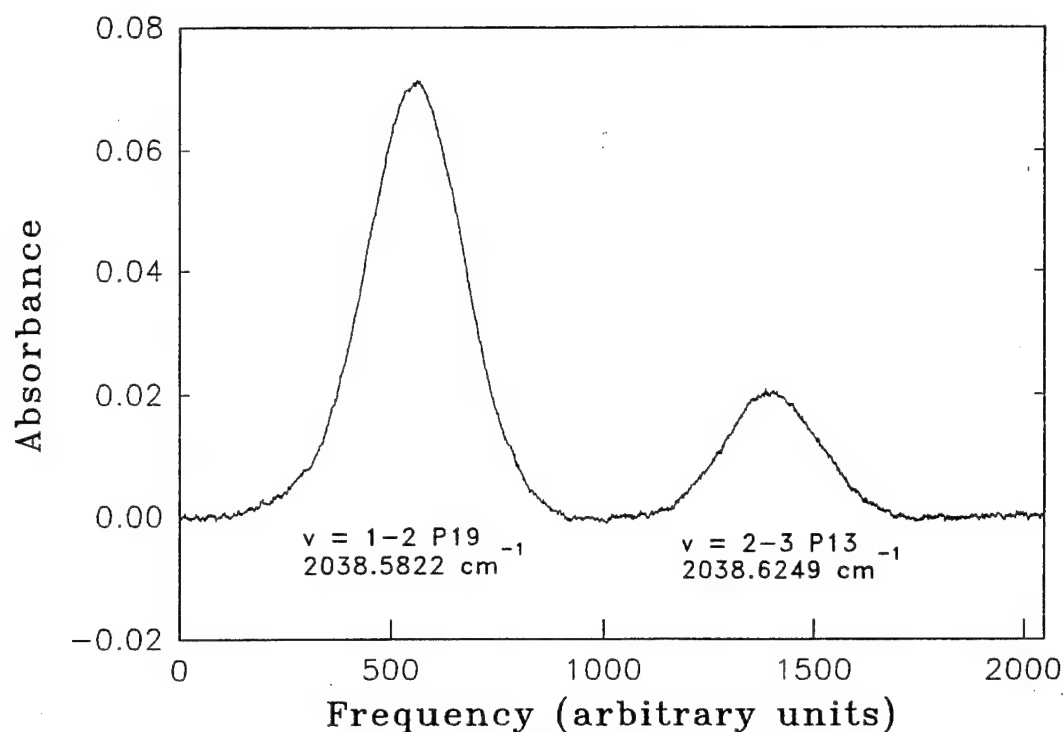


Figure 4. CO hot band absorbance in a 20-torr stoichiometric methane/oxygen flame.

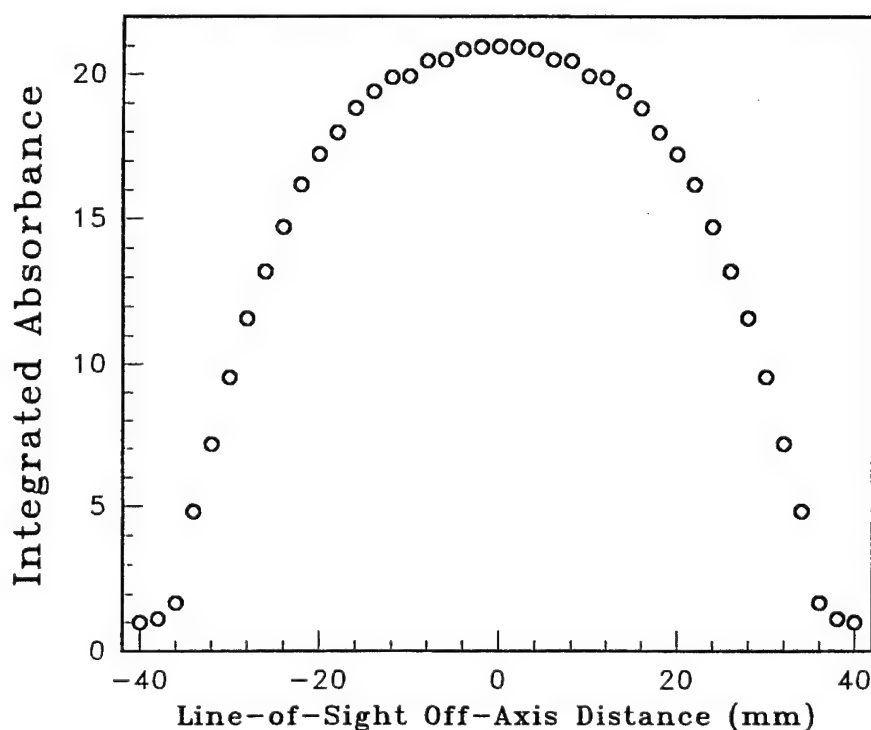


Figure 5. Line-of-sight integrated absorbance for CO P19 ($\nu=1\rightarrow2$) in a 20-torr stoichiometric methane/oxygen flame as a function of off-axis distance using a laser beam diameter of 0.8 mm. All spectra were measured through a plane lying 5.2 mm above the burner surface. The edge of the burner is at -30 and 30 mm. Data have been reflected about the burner axis.

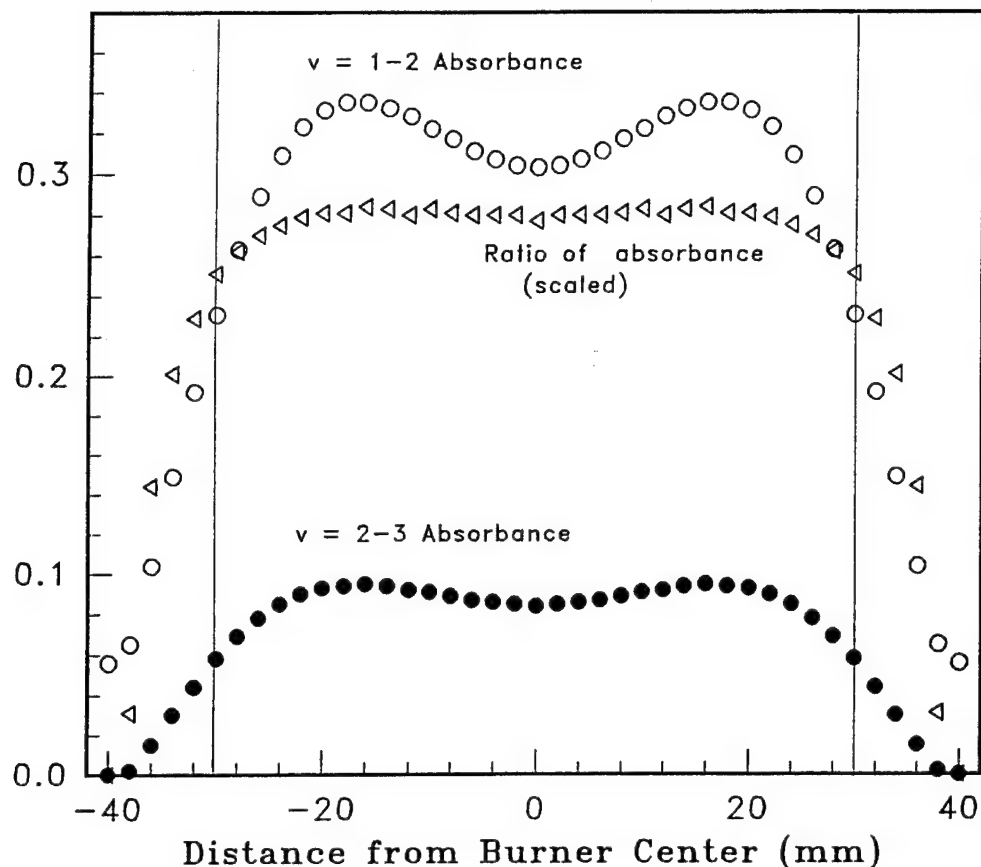


Figure 6. Results of tomographic analysis on line-of-sight CO absorbance spectra lying in a plane 0.8 mm thick and 4.19 mm above the burner surface for a 20-torr stoichiometric methane/oxygen flame. Note that a constant temperature is seen across the burner face even though the populations of P19 ($v=1 \rightarrow 2$) and P13 ($v=2 \rightarrow 3$) are not constant. Data have been reflected about the burner axis.

the flame. It is observed that the temperature in the flame within the line-of-sight plane is fairly constant even though the population of excited states varies with radial position. A conclusion from this figure is that the assumption of uniform concentration or population distribution at a given height in the flame based upon uniform temperature at that height is questionable. Although nonuniformity at a given height across a "flat" flame has been observed previously (Jeffries et al. 1992) for species other than CO, to our knowledge this is the first observation of this phenomenon using a line-of-sight technique. Calculations are currently underway to determine if radial variations in temperatures or radial species are responsible for the radial variation in CO excited state populations.

Finally, from Figure 6, it may be seen that population in the first excited vibrational state of CO extends further outside the flame region than does population in the second excited vibrational state. The

fraction of the area under the curves for localized $v=1 \rightarrow 2$ and $v=2 \rightarrow 3$ absorbance in Figure 6 that lies within the flame zone cylinder defined by the burner circumference is $0.88 (\pm 0.01)$ and $0.92 (\pm 0.02)$, respectively. Figure 7 shows the fraction of line-of-sight $v=1 \rightarrow 2$ absorbance in a 20-torr CH_4/O_2 flame that lies within the cylinder defined by the burner circumference as a function of height above the burner surface and the best linear fit to the data. The best linear fit within the region defined by the burner diameter (60 mm) is given by

$$y = -0.012x + 0.94 \quad (3)$$

where y is the fraction of $v=1 \rightarrow 2$ absorbance within the flame region and x is the height in millimeters above the burner surface of the line of sight. The uncertainty in the slope in Equation 3 is ± 0.001 . Figure 8 shows the fraction of line-of-sight $v=2 \rightarrow 3$ absorbance within the 20-torr premixed CH_4/O_2 flame as a function of height above the burner surface along with the best linear fit to the data. The analogous equation to Equation 3 is

$$y = -0.0085x + 0.97. \quad (4)$$

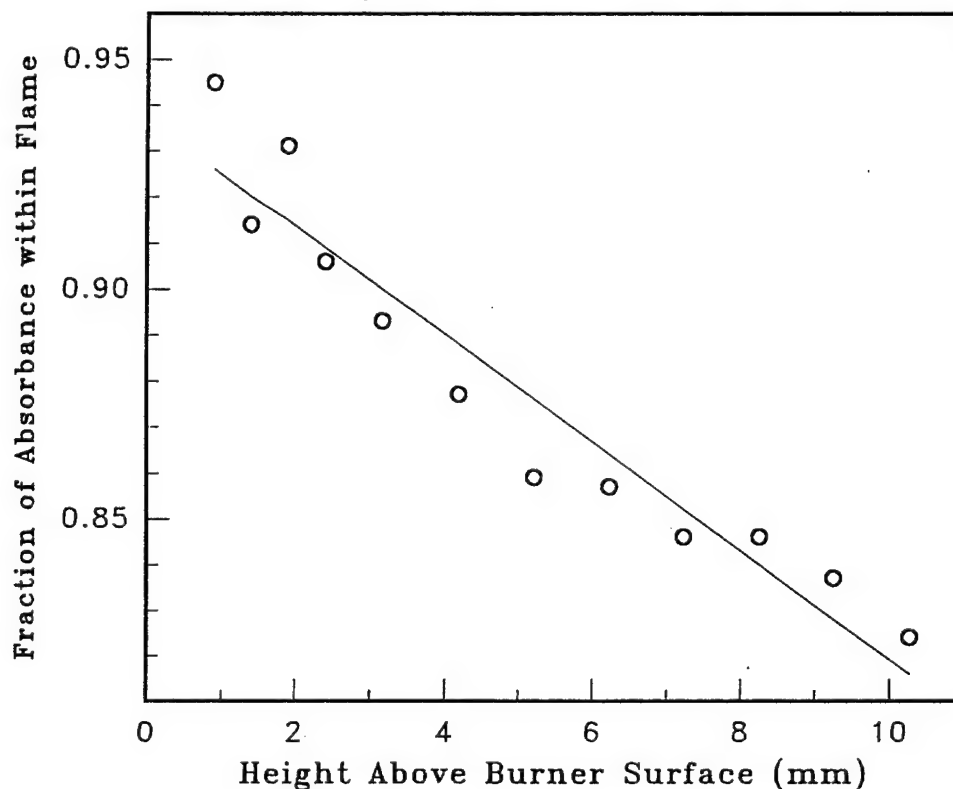


Figure 7. The fraction of CO $v=1 \rightarrow 2$ absorbance that lies within the flame region as a function of height above the burner surface for a 20-torr stoichiometric methane/oxygen flame.

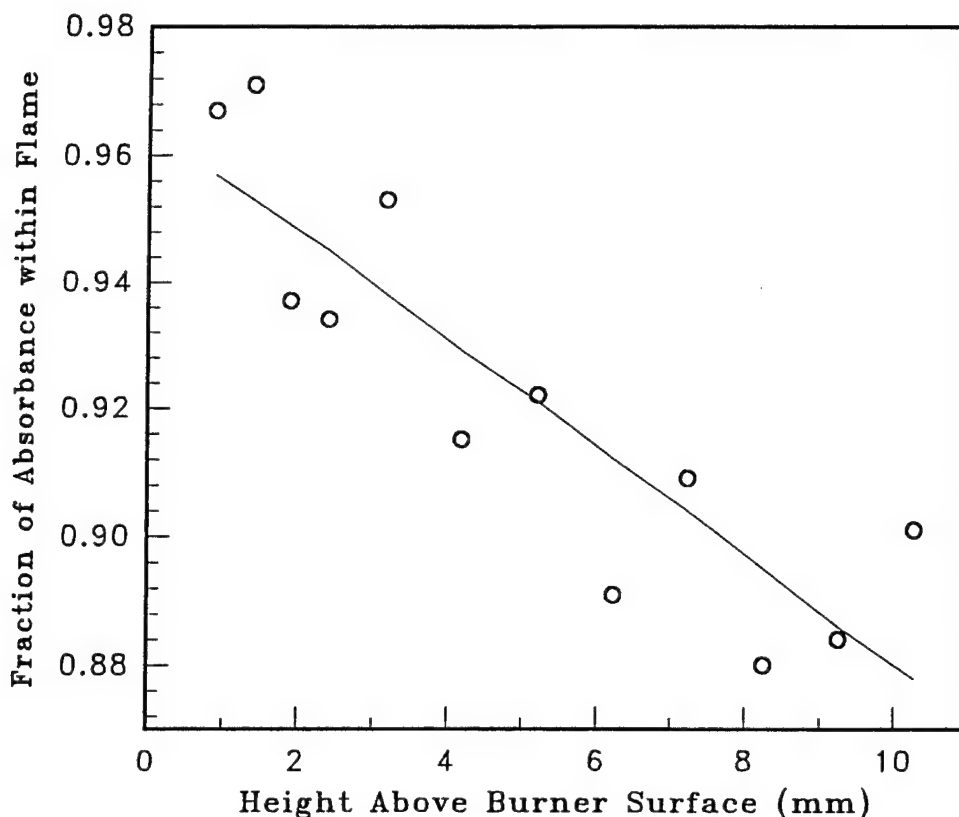


Figure 8. The fraction of CO $v=2 \rightarrow 3$ absorbance that lies within the flame region as a function of height above the burner surface for a 20-torr stoichiometric methane/oxygen flame.

The uncertainty in the slope in Equation 4 is ± 0.0014 . Again, it should be emphasized that this correction applies only to the flame region defined by the burner diameter (60 mm). For line-of-sight spectra over the region studied here (0–10 mm above the burner surface), Equations 3 and 4 indicate that as distance from the burner surface increases, the amount of $v=1 \rightarrow 2$ absorbance that lies outside the flame increases at a faster rate than does the amount of $v=2 \rightarrow 3$ absorbance that lies outside the flame. The effect is that at any height above the burner surface, the observed line-of-sight $v=1 \rightarrow 2$ integrated absorbance is in error to a greater degree than the observed line-of-sight $v=2 \rightarrow 3$ integrated absorbance. For each transition, an excess of integrated absorbance is always observed. Since the temperature is a nonlinear function of the ratio of the integrated absorbance of the $v=2 \rightarrow 3$ transition to the $v=1 \rightarrow 2$ transition (Herzberg 1950), the observed temperature is always too low and the correction to the observed temperature is not directly proportional to the height above the burner surface. This effect has been predicted (Ouyang and Varghese 1989) but has not been demonstrated previously by experiment.

Figure 9 shows the temperature data presented in Figure 2 together with the line-of-sight temperature data to which corrections according to Equations 3 and 4 have been applied. In general, the primary effect of the line-of-sight correction is to shift the uncorrected temperature to a higher value. The secondary effect of the correction (because of the differing values of the slopes in Equations 3 and 4) is to shift the peak temperature further from the burner surface. Also, for the two-line thermometry experiments, sensitivity decreases as the difference in initial energy states for the two transitions ($E''_2 - E''_1$) approaches kT . For the transitions used in these experiments, this situation exists near the peak measured temperature. It is possible that better data would be obtained by repeating the experiments using transitions for which initial states differ by more than one vibrational quantum number. Another possible reason for the remaining discrepancy between corrected two-line thermometry measurements and thermocouple measurements is that the linear fit to the data in Figures 7 and 8 is inappropriate and instead a nonlinear fit to the data should be used. In this case, it would be necessary to do tomographic analysis of line-of-sight spectra over a greater vertical range than has been done here. Still, the net result of the correction is to bring the line-of-sight based temperature measurements into better agreement with thermocouple measurements. Also, it has been suggested that since the final "burned gas" temperatures are in good agreement, it is possible that the discrepancy between thermocouple and optically measured temperatures in the flame region are due to perturbations of the flame chemistry by the thermocouple. Our experiences with thermocouple measurements indicate that this is probably not the case for the experiments reported here. Finally, it is possible that horizontal movement of the burner within the low pressure chamber may disturb the flow of gas outside of the burner region. We have assumed no appreciable effect of burner translation, but have not been able to verify this assumption.

5. CONCLUSION

Two main conclusions may be drawn from this work. First, it has been shown that when using line-of-sight two-line thermometry to examine low-pressure flames, the observed temperature is always too low and the correction that must be applied to the observed temperature is a nonlinear function of the height above the burner surface. This is because there is a radial spread of the flame beyond the burner radius, imparting a 2-D structure to the flame. It has been shown that constant temperature across a flame at a given height in the flame does not imply constant species concentration across the flame at that height. Finally, for low-pressure work (<20-torr total pressure) where two-line thermometry is employed, it is recommended that some type of tomographic analysis of line-of-sight data be performed to obtain a functional relationship between absorbance outside of the flame region and height above the burner surface

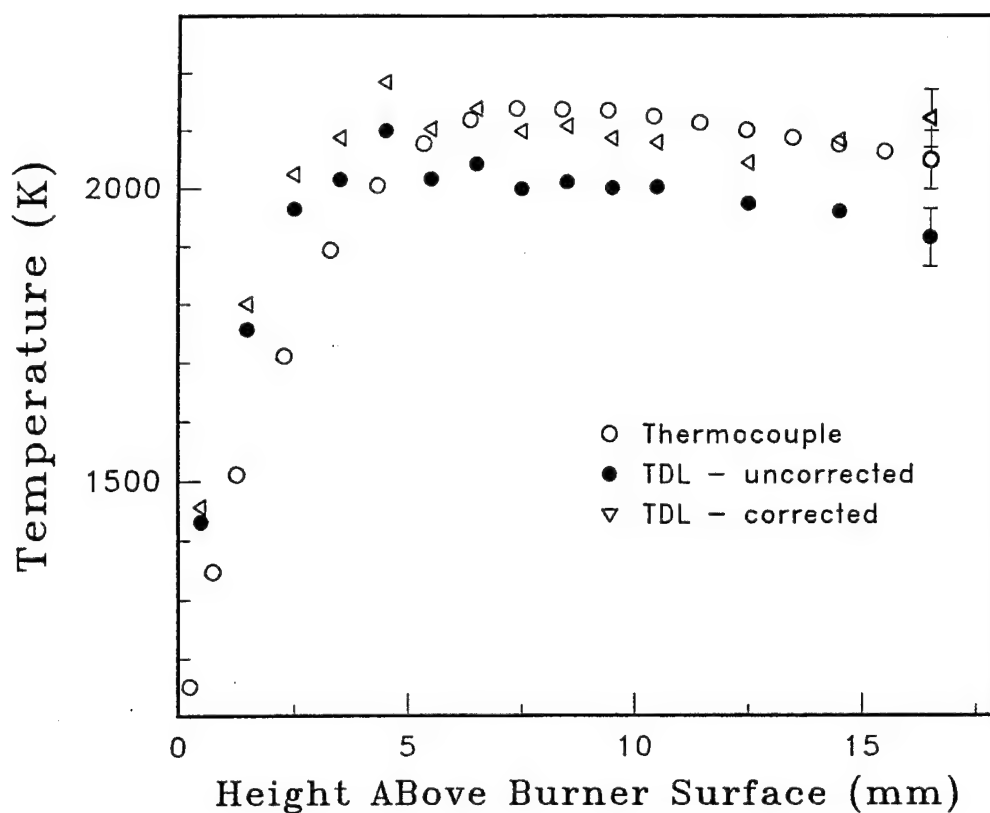


Figure 9. Uncorrected and corrected flame temperatures measured using line-of-sight two-line thermometry and using thermocouples as a function of height above the burner surface for a 20-torr stoichiometric methane/oxygen flame.

for the two transitions involved in the calculation. We believe that as multidimensional detector arrays become more affordable, tomographic analysis will become an important tool for routine investigations of combusting systems.

6. REFERENCES

- Best, P. E., P. L. Chien, R. M. Carangelo, P. R. Solomon, M. Danchak, and I. Ilovici. "Tomographic Reconstruction of FT-IR Emission and Transmission Spectra in a Sooting Laminar Diffusion Flame: Species Concentrations and Temperatures." Combustion and Flame, vol. 85, pp. 309-318, 1991.
- Cormack, A. M. "Representation of a Function By Its Line Integrals, With Some Radiological Implications." Journal of Applied Physics, vol. 34, pp. 2722-2727, 1963.
- Dasch, C. J. "One-Dimensional Tomography: A Comparison of Abel, Onion-Peeling, and Filtered Backprojection Methods." Applied Optics, vol. 31, pp. 1146-1152, 1992.
- Dayton, D. C., R. C. Sausa, A. J. Kotlar, and A. W. Miziolek. "A Novel Flame Thermometer Based on the Doppler Width of Rovibrational Transitions." ARL-TR-129, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, May 1993.
- Deutsch, M., and I. Beniaminy. "Inversion of Abel's Integral Equation for Experimental Data." J. Applied Physics, vol. 54, pp. 137-143, 1983.
- Guelachvili, G., and K. N. Rao. Handbook of Infrared Standards. Orlando, Florida: Academic Press, 1986.
- Hanson, R. K., and P. K. Falcone. "Temperature Measurement Technique for High-Temperature Gases Using a Tunable Diode Laser." Applied Optics, vol. 17, pp. 2477-2480, 1978.
- Herzberg, G. Infrared and Raman Spectra. New York: Van Nostrand, 1950.
- Hughey, B. J., and D. A. Santavicca. "A Comparison of Techniques for Reconstructing Axisymmetric Reacting Flow Fields From Absorption Measurements." Combustion and Science Technology, vol. 29, pp. 167-190, 1982.
- Jeffries, J. B., G. P. Smith, D. E. Heard, and D. R. Crosley. "Comparing Laser-Induced Fluorescence Measurements and Computer Models of Low-Pressure Flame Chemistry." Ber. Bunsenges. Phys. Chem., vol. 96, pp. 1410-1416, 1992.
- Kent, J. H. "A Noncatalytic Coating for Platinum-Rhodium Thermocouples." Combustion and Flame, vol. 14, pp. 279-281, 1970.
- Limbaugh, C. C. "The Infrared Emission - Absorption Method for Temperature and Species Partial Pressure Determination in Flames and Plumes" in Infrared Methods for Gaseous Measurements. Optical Engineering, vol. 7, pp. 197-246, edited by J. Wormhoudt, New York: Marcel Dekker, Inc., 1985.
- McNesby, K. L., and R. A. Fifer. "Tomographic Reconstruction of Infrared Spectra of Non-Homogeneous Media: Applications to a Flat Flame Burner." BRL-TR-3333, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, April 1992.

Ouyang, X. and P. L. Varghese. "Line-of-Sight Absorption Measurements of High Temperature Gases With Thermal and Concentration Boundary Layers." Applied Optics, vol. 28, pp. 3979-3984, 1989.

Ouyang, X., and P. L. Varghese. "Selection of Spectral Lines for Combustion Diagnostics." Applied Optics, vol. 29, pp. 4884-4890, 1990.

Rothman, L. S., R. R. Gamache, R. H. Tipping, C. P. Rinsland, M. A. H. Smith, D. C. Benner, V. Malathy Devi, J. -M. Flaud, C. Camy-Peyert, A. Perrin, A. Goldman, S. T. Massie, L. R. Brown, and R. A. Toth. J. Quant. Spectrosc. Radiat. Transfer, vol. 48, p. 469, 1992 (1992 HITRAN database).

Sausa, R. C., S. L. Howard, R. J. Locke, A. J. Kotlar, and A. W. Miziolek. "Chemical and Physical Processes in Combustion." Proceedings of the Fall Technical Meeting of the Eastern Section of the Combustion Institute, p. 108-1, 1990.

Schoenung, S. M., and R. K. Hanson. "CO and Temperature Measurements in a Flat Flame by Laser Absorption Spectroscopy and Probe Techniques." Combustion Science and Technology, vol. 24, pp. 227-237, 1981.

Todd, T. R., C. M. Clayton, W. B. Telfair, T. K. McCubbin, and J. Pli'va. "Infrared Emission of $C^{12}O^{16}$, $C^{13}O^{16}$, and $C^{12}O^{18}$." J. Mol. Spec., vol. 62, pp. 201-227, 1976.

Varghese, P. L., and R. K. Hanson. "Tunable Infrared Diode Laser Measurements of Line Strengths and Collision Widths of $^{12}C^{16}O$ at Room Temperature." J. Quant. Spectrosc. Radiat. Transfer, vol. 24, pp. 479-489, 1980.

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	ADMINISTRATOR ATTN DTIC DDA DEFENSE TECHNICAL INFO CTR CAMERON STATION ALEXANDRIA VA 22304-6145
1	DIRECTOR ATTN AMSRL OP SD TA US ARMY RESEARCH LAB 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	DIRECTOR ATTN AMSRL OP SD TL US ARMY RESEARCH LAB 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DIRECTOR ATTN AMSRL OP SD TP US ARMY RESEARCH LAB 2800 POWDER MILL RD ADELPHI MD 20783-1145
<u>ABERDEEN PROVING GROUND</u>	
5	DIR USARL ATTN AMSRL OP AP L (305)

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	HQDA ATTN SARD TT DR F MILTON PENTAGON WASHINGTON DC 20310-0103
1	HQDA ATTN SARD TT MR J APPEL PENTAGON WASHINGTON DC 20310-0103
1	HQDA OASA RDA ATTN DR C H CHURCH PENTAGON ROOM 3E486 WASHINGTON DC 20310-0103
4	COMMANDER ATTN R GHIRARDELLI D MANN R SINGLETON R SHAW US ARMY RESEARCH OFFICE P O BOX 12211 RSCH TRNGLE PK NC 27709-2211
1	DIRECTOR ATTN AMXRO MCS K CLARK ARMY RESEARCH OFFICE P O BOX 12211 RSCH TRNGLE PK NC 27709-2211
1	DIRECTOR ATTN AMXRO RT IP LIB SERVICES ARMY RESEARCH OFFICE P O BOX 12211 RSCH TRNGLE PK NC 27709-2211
2	COMMANDER ATTN SMCAR AEE B D S DOWNS US ARMY ARDEC PCTNY ARSNL NJ 07806-5000
2	COMMANDER ATTN SMCAR AEE J A LANNON US ARMY ARDEC PCTNY ARSNL NJ 07806-5000
1	COMMANDER ATTN SMCAR AEE BR L HARRIS US ARMY ARDEC PCTNY ARSNL NJ 07806-5000

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	COMMANDER ATTN AMSMI RD PR E A R MAYKUT AMSMI RD PR P R BETTS US ARMY MISSILE COMMAND REDSTONE ARSENAL AL
1	OFFICE OF NAVAL RESEARCH DEPARTMENT OF THE NAVY ATTN R S MILLER CODE 432 800 N QUINCY STREET ARLINGTON VA 22217
1	COMMANDER ATTN J RAMNARACE AIR 54111C NAVAL AIR SYSTEMS COMMAND WASHINGTON DC 20360
2	COMMANDER ATTN R BERNECKER R 13 G B WILMOT R 16 NAVAL SURFACE WARFARE CENTER SILVER SPRING MD 20903-5000
5	COMMANDER ATTN M C LIN J MCDONALD E ORAN J SHNUR R J DOYLE CODE 6110 NAVAL RESEARCH LABORATORY WASHINGTON DC 20375
2	COMMANDER ATTN T BOGGS CODE 388 T PARR CODE 3895 NAVAL WEAPONS CENTER CHINA LAKE CA 93555-6001
1	SUPERINTENDENT ATTN D W NETZER DEPT OF AERONAUTICS NAVAL POSTGRADUATE SCHOOL MONTEREY CA 93940
3	AL LSCF ATTN R CORLEY R GEISLER J LEVINE EDWARDS AFB CA 93523-5000

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	AFOSR ATTN J M TISHKOFF BOLLING AIR FORCE BASE WASHINGTON DC 20332
1	OSD SDIO IST ATTN L CAVENY PENTAGON WASHINGTON DC 20301-7100
1	COMMANDANT ATTN ATSF TSM CN USAFAS FORT SILL OK 73503-5600
1	UNIV OF DAYTON RSCH INSTITUTE ATTN D CAMPBELL AL PAP EDWARDS AFB CA 93523
1	NASA ATTN G B NORTHAM MS 168 LANGLEY RESEARCH CENTER LANGLEY STATION HAMPTON VA 23365
4	NATIONAL BUREAU OF STANDARDS ATTN J HASTIE M JACOX T KASHIWAGI H SEMERJIAN US DEPARTMENT OF COMMERCE WASHINGTON DC 20234
2	DIRECTOR ATTN C WESTBROOK W TAO MS L 282 LAWRENCE LIVERMORE NATIONAL LAB P O BOX 808 LIVERMORE CA 94550
1	DIRECTOR ATTN B NICHOLS T7 MS B284 LOS ALAMOS NATIONAL LAB P O BOX 1663 LOS ALAMOS NM 87545

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	PRINCETON COMBUSTION RESEARCH LABORATORIES INC ATTN N A MESSINA M SUMMERFIELD PRINCETON CORPORATE PLAZA BLDG IV SUITE 119 11 DEERPARK DRIVE MONMOUTH JUNCTION NJ 08852
3	DIRECTOR DIVISION 8354 ATTN S JOHNSTON P MATTERN D STEPHENSON SANDIA NATIONAL LABORATORIES LIVERMORE CA 94550
1	BRIGHAM YOUNG UNIVERSITY ATTN M W BECKSTEAD DEPT OF CHEMICAL ENGINEERING PROVO UT 84058
1	CALIFORNIA INSTITUTE OF TECH JET PROPULSION LABORATORY ATTN L STRAND MS 125 224 4800 OAK GROVE DRIVE PASADENA CA 91109
1	CALIFORNIA INSTITUTE OF TECHNOLOGY ATTN F E C CULICK MC 301 46 204 KARMAN LAB PASADENA CA 91125
1	UNIVERSITY OF CALIFORNIA LOS ALAMOS SCIENTIFIC LAB P O BOX 1663 MAIL STOP B216 LOS ALAMOS NM 87545
1	UNIVERSITY OF CALIFORNIA BERKELEY CHEMISTRY DEPARMENT ATTN C BRADLEY MOORE 211 LEWIS HALL BERKELEY CA 94720
1	UNIVERSITY OF CALIFORNIA SAN DIEGO ATTN F A WILLIAMS AMES B010 LA JOLLA CA 92093

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	UNIV OF CALIFORNIA SANTA BARBARA QUANTUM INSTITUTE ATTN K SCHOFIELD M STEINBERG SANTA BARBARA CA 93106
1	UNIV OF COLORADO AT BOULDER ENGINEERING CENTER ATTN J DAILY CAMPUS BOX 427 BOULDER CO 80309-0427
3	UNIV OF SOUTHERN CALIFORNIA DEPT OF CHEMISTRY ATTN R BEAUDET S BENSON C WITTIG LOS ANGELES CA 90007
1	CORNELL UNIVERSITY DEPARTMENT OF CHEMISTRY ATTN T A COOL BAKER LABORATORY ITHACA NY 14853
1	UNIVERSITY OF DELAWARE ATTN T BRILL CHEMISTRY DEPARTMENT NEWARK DE 19711
1	UNIVERSITY OF FLORIDA ATTN J WINEFORDNER DEPT OF CHEMISTRY GAINESVILLE FL 32611
3	GEORGIA INSTITUTE OF TECHNOLOGY SCHOOL OF AEROSPACE ENGINEERING ATTN E PRICE W C STRAHLE B T ZINN ATLANTA GA 30332
1	UNIVERSITY OF ILLINOIS DEPT OF MECH ENG ATTN H KRIER 144MEB 1206 W GREEN ST URBANA IL 61801
1	THE JOHNS HOPKINS UNIV CPIA ATTN T W CHRISTIAN 10630 LITTLE PATUXENT PKWY SUITE 202 COLUMBIA MD 21044-3200

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	UNIVERSITY OF MICHIGAN GAS DYNAMICS LAB ATTN G M FAETH AEROSPACE ENGINEERING BLDG ANN ARBOR MI 48109-2140
1	UNIVERSITY OF MINNESOTA DEPT OF MECHANICAL ENGINEERING ATTN E FLETCHER MINNEAPOLIS MN 55455
4	PENNSYLVANIA STATE UNIVERSITY DEPT OF MECHANICAL ENGINEERING ATTN K KUO M MICCI S THYNELL V YANG UNIVERSITY PARK PA 16802
2	PRINCETON UNIVERSITY FORRESTAL CAMPUS LIBRARY ATTN K BREZINSKY I GLASSMAN P O BOX 710 PRINCETON NJ 08540
1	PURDUE UNIVERSITY SCHOOL OF AERONAUTICS AND ASTRONAUTICS ATTN J R OSBORN GRISSOM HALL WEST LAFAYETTE IN 47906
1	PURDUE UNIVERSITY DEPARTMENT OF CHEMISTRY ATTN E GRANT WEST LAFAYETTE IN 47906
2	PURDUE UNIVERSITY SCHOOL OF MECHANICAL ENGINEERING ATTN N M LAURENDEAU S N B MURTHY TSPC CHAFFEE HALL WEST LAFAYETTE IN 47906
1	RENSSELAER POLYTECHNIC INST DEPT OF CHEMICAL ENGINEERING ATTN A FONTIJN TROY NY 12181

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	STANFORD UNIVERSITY DEPT OF MECHANICAL ENGINEERING ATTN R HANSON STANFORD CA 94305
1	UNIVERSITY OF TEXAS DEPT OF CHEMISTRY ATTN W GARDINER AUSTIN TX 78712
1	VA POLYTECH INST AND STATE UNIV ATTN J A SCHETZ BLACKSBURG VA 24061
1	APPLIED COMBUSTION TECHNOLOGY INC ATTN A M VARNEY P O BOX 607885 ORLANDO FL 32860
2	APPLIED MECHANICS REVIEWS ASME ATTN R E WHITE & A B WENZEL 345 E 47TH STREET NEW YORK NY 10017
1	ATLANTIC RESEARCH CORP ATTN R H W WAESCHE 7511 WELLINGTON ROAD GAINESVILLE VA 22065
1	TEXTRON DEFENSE SYSTEMS ATTN A PATRICK 2385 REVERE BEACH PARKWAY EVERETT MA 02149-5900
1	BATTELLE TWSTIAC 505 KING AVENUE COLUMBUS OH 43201-2693
1	COHEN PROFESSIONAL SERVICES ATTN N S COHEN 141 CHANNING STREET REDLANDS CA 92373
1	EXXON RESEARCH & ENG CO ATTN A DEAN ROUTE 22E ANNANDALE NJ 08801

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	GENERAL APPLIED SCIENCE LABS INC 77 RAYNOR AVENUE RONKONKAMA NY 11779-6649
1	GENERAL ELECTRIC ORDNANCE SYSTEMS ATTN J MANDZY 100 PLASTICS AVENUE PITTSFIELD MA 01203
1	GENERAL MOTORS RSCH LABS PHYSICAL CHEMISTRY DEPARTMENT ATTN T SLOANE WARREN MI 48090-9055
2	HERCULES INC ATTN W B WALKUP E A YOUNT P O BOX 210 ROCKET CENTER WV 26726
1	HERCULES INC ATTN R V CARTWRIGHT 100 HOWARD BLVD KENVIL NJ 07847
1	ALLIANT TECHSYSTEMS INC MARINE SYSTEMS GROUP ATTN D E BRODEN MS MN50 2000 600 2ND STREET NE HOPKINS MN 55343
1	ALLIANT TECHSYSTEMS INC ATTN R E TOMPKINS MN 11 2720 600 SECOND ST NORTH HOPKINS MN 55343
1	IBM CORPORATION ATTN A C TAM RESEARCH DIVISION 5600 COTTLE ROAD SAN JOSE CA 95193
1	IIT RESEARCH INSTITUTE ATTN R F REMALY 10 WEST 35TH STREET CHICAGO IL 60616

NO. OF
COPIES ORGANIZATION

1 LOCKHEED MISSILES & SPACE CO
ATTN GEORGE LO
3251 HANOVER STREET
DEPT 52 35 B204 2
PALO ALTO CA 94304

1 OLIN ORDNANCE
ATTN V MCDONALD LIBRARY
P O BOX 222
ST MARKS FL 32355-0222

1 PAUL GOUGH ASSOCIATES INC
ATTN P S GOUGH
1048 SOUTH STREET
PORTSMOUTH NH 03801-5423

1 HUGHES AIRCRAFT COMPANY
ATTN T E WARD
8433 FALLBROOK AVENUE
CANOGA PARK CA 91303

1 ROCKWELL INTERNATIONAL CORP
ROCKETDYNE DIVISION
ATTN J E FLANAGAN HB02
6633 CANOGA AVENUE
CANOGA PARK CA 91304

1 SCIENCE APPLICATIONS INC
ATTN R B EDELMAN
23146 CUMORAH CREST
WOODLAND HILLS CA 91364

3 SRI INTERNATIONAL
ATTN G SMITH
D CROSLEY
D GOLDEN
333 RAVENSWOOD AVENUE
MENLO PARK CA 94025

1 STEVENS INSTITUTE OF TECH
DAVIDSON LABORATORY
ATTN R MCALEVY III
HOBOKEN NJ 07030

1 SVERDRUP TECHNOLOGY INC
LERC GROUP
ATTN R J LOCKE MS SVR 2
2001 AEROSPACE PARKWAY
BROOK PARK OH 44142

NO. OF
COPIES ORGANIZATION

1 SVERDRUP TECHNOLOGY INC
ATTN J DEUR
2001 AEROSPACE PARKWAY
BROOK PARK OH 44142

3 THIOKOL CORPORATION
ELKTON DIVISION
ATTN R BIDDLE
R WILLER
TECH LIB
P O BOX 241
ELKTON MD 21921

3 THIOKOL CORPORATION
WASATCH DIVISION
ATTN S J BENNETT
P O BOX 524
BRIGHAM CITY UT 84302

1 UNITED TECHNOLOGIES RSCH CENTER
ATTN A C ECKBRETH
EAST HARTFORD CT 06108

1 UNITED TECHNOLOGIES CORP
CHEMICAL SYSTEMS DIVISION
ATTN R R MILLER
P O BOX 49028
SAN JOSE CA 95161-9028

1 UNIVERSAL PROPULSION COMPANY
ATTN H J MCSPADDEN
25401 NORTH CENTRAL AVENUE
PHOENIX AZ 85027-7837

1 VERITAY TECHNOLOGY INC
ATTN E B FISHER
4845 MILLERSPORT HIGHWAY
EAST AMHERST NY 14051-0305

1 FREEDMAN ASSOCIATES
ATTN E FREEDMAN
2411 DIANA ROAD
BALTIMORE MD 21209-1525

1 ALLIANT TECHSYSTEMS
ATTN J BODE
600 SECOND ST NE
HOPKINS MN 55343

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	ALLIANT TECHSYSTEMS ATTN C CANDLAND 600 SECOND ST NE HOPKINS MN 55343
1	ALLIANT TECHSYSTEMS ATTN L OSGOOD 600 SECOND ST NE HOPKINS MN 55343
1	ALLIANT TECHSYSTEMS ATTN R BURETTA 600 SECOND ST NE HOPKINS MN 55343
1	ALLIANT TECHSYSTEMS ATTN R BECKER 600 SECOND ST NE HOPKINS MN 55343
1	ALLIANT TECHSYSTEMS ATTN M SWENSON 600 SECOND ST NE HOPKINS MN 55343
1	US ARMY BENET LABORATORY ATTN SAM SOPOK SMCAR CCB B WATERVLIET NY 12189

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
	<u>ABERDEEN PROVING GROUND</u>
36	DIR USARL ATTN: AMSRL-WT-P, A HORST AMSRL-WT-PC, R A FIFER G F ADAMS W R ANDERSON R A BEYER S W BUNTE C F CHABALOWSKI K P MC-NEILL BOONSTOPPEL A COHEN R CUMPTON R DANIEL D DEVYNCK N F FELL B E FORCH J M HEIMERL A J KOTLAR M R MANAA W F MCBRATNEY K L MCNESBY S V MEDLIN M S MILLER A W MIZIOLEK S H MODIANO J B MORRIS J E NEWBERRY S A NEWTON R A PESCE-RODRIGUEZ B M RICE R C SAUSA M A SCHROEDER J A VANDERHOFF M WENSING A WHREN J M WIDDER C WILLIAMSON AMSRL-CI-CA, R PATEL

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number ARL-TR-769 Date of Report June 1995
2. Date Report Received _____
3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) _____

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) _____

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. _____

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) _____

CURRENT ADDRESS

Organization

Name

Street or P.O. Box No.

City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD ADDRESS

Organization

Name

Street or P.O. Box No.

City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)
(DO NOT STAPLE)

DEPARTMENT OF THE ARMY

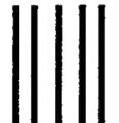
OFFICIAL BUSINESS

BUSINESS REPLY MAIL

FIRST CLASS PERMIT NO 0001,APG,MD

POSTAGE WILL BE PAID BY ADDRESSEE

DIRECTOR
U.S. ARMY RESEARCH LABORATORY
ATTN: AMSRL-WT-PC
ABERDEEN PROVING GROUND, MD 21005-5066



NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES

